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FINAL REPORT ON THE DEMONSTRATION OF ENERGY PRODUCTION AND CONSERVATION BY ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION OF SWINE MANURE

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1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

During the past thirty years, both the size and intensity of farming operations in North America have increased. During the same period, the livestock industry has become more highly energy dependent through the extensive use of mechanized equipment operating on fossil fuels and electricity. While no shortage of energy is anticipated in Canada in the near future, recent, and projected energy cost increases have made farm management more aware of the energy component of their operating costs.

As Canadian farms increase in size and the rural-urban interface narrows, odour reduction and pollution control is becoming an area of concern for many producers. The economic impact of pollution control on farming activities is difficult to determine. However, the regulation of farming activities and enforcement of environmental codes of practice will undoubtedly increase the cost of farm pollution control during the next decade.

Anaerobic Digestion is one technology that has the potential to reduce the cost of energy on medium to large scale agricultural operations, while providing a significant reduction of environmental pollution (primarily odour) from farming activities.

While anaerobic digestion technology has been proven at farm scale at Roslyn Park Farm, a beef feedlot in Southern Ontario (CANVIRO, 1982), and at Selves Farm Limited, a swine operation in Southern Ontario (CANVIRO, 1984), the Linden Lee Farms system represents the first application of this technology on a swine operation in Eastern Canada.

1.2 Project Background

During 1982, CANVIRO Consultants Ltd. was awarded a contract from the National Research Council, Prairie Regional Laboratory, Saskatoon, to complete the third year of a three year study of Anaerobic Digestion and Protein Recovery from Livestock Manures. The overall objectives of the final year of the study were to provide valuable scale-up data between the Roslyn Park Farm (RPF) full-scale (635 m^3) digester and the laboratory-scale (0.025 m^3) digesters used for the manure treatability assessment, and to investigate the anaerobic digestion potential of a typical swine manure. Specific objectives of the study were:

(i) To provide scale-up data between the laboratory and full-scale digesters by operating them under similar conditions for both mesophilic and thermophilic anaerobic digestion.

(ii) To investigate the digestion and protein recovery potential of swine waste, and to delineate the design parameters for a full-scale facility.

(iii) To evaluate the operation of laboratory-scale digestion units on manures from beef feedlots feeding more conventional rations than the RPF ration, and to determine the effect of the ration on the process design for the digestion system.

(iv) To evaluate the effectiveness of thermophilic and mesophilic digestion on the survival of various indicator pathogenic organisms.

The following conclusions about swine manure were made based on this study:

(1) Swine manure is very amenable to anaerobic digestion.

(2) Mesophilic digester operation was more stable and energy efficient than thermophilic operation on both swine and beef manures.

(3) Biogas production and quality were generally superior when swine manure was collected after the solids separator than before. Higher loading rates could be achieved with manure after solids separation. Mesophilic digestion of swine manure after solids separation was highly successful at a HRT as short as 7.5 days.

(4) Thermophilic fermentation of swine manure was unstable and difficult to control, probably due to free ammonia toxicity.

(5) The 25 L digesters provided direct scale-up of biogas quantity and quality when compared to the full-scale RPF fermenter. Other individual parameters such as volatile acids, bicarbonate alkalinity and pH indicated slightly more stable operation during full-scale digestion than predicted by the results at laboratory-scale.

On the basis of this study in April, 1982, CANVIRO prepared a proposal to construct a full-scale Anaerobic Digestion and Electrical Co-Generation System at Linden Lee Farms, PEI.

In April, 1983, Energy, Mines and Resources provided funding support through the Conservation of Renewable Energy Demonstration Program (CREDA), and signed a contract with Linden Lee Farms to provide 66-2/3% funding of the capital costs of the system, and to fund the engineering and performance monitoring of the system for approximately 4 months.

This report summarizes the design criteria for the full-scale system, a summary of the four month monitoring program and an energy and economic assessment of the project.

2.0 FULL-SCALE DESIGN

2.1 Design Considerations

2.1.1 Anaerobic Digester Design

The two primary design considerations for anaerobic digestion systems are (1) the organic loading rate and (2) the hydraulic loading rate or theoretical liquid retention time. The maximum organic loading rate and the minimum hydraulic retention times should be determined by the operation of laboratory-scale digestion units on representative samples of the waste (manure).

The organic loading rate is generally expressed in terms of kilograms of chemical oxygen demand (COD) or kilograms of volatile residual solids fed to the digester per unit of digester volume per unit of time (i.e. kg VS/m^3/d). The organic loading rate is used as a measure of the substrate available for conversion to biogas.

The specific gas (biogas or methane) production rate, expressed in cubic meters of gas produced per unit of volatile solids or chemical oxygen demand fed per day, and the volatile solids or chemical oxygen demand removal efficiency are used to measure the effect of organic and hydraulic loading rates on digester performance.

In general, a trade off between volatile solids or chemical oxygen demand removal efficiency and specific biogas production rate can be made with organic loading rate and hydraulic retention time. As the organic loading rate to the digestion system is increased (i.e. shorter hydraulic retention time), the specific biogas production and removal efficiencies decrease. In practical design, a trade off between digester capital cost and the biogas utilization revenue (savings) should be optimized. Pilot-scale laboratory studies conducted on swine manure (CANVIRO, 1982) indicated that organic loading rates up to 4.5 kg VS/m^3/day could be processed with only a small reduction in the specific gas production rate (m^3 biogas at STP/kg VS fed/d) and the volatile solids removal efficiency.

An economic assessment of a completely mixed vs. a fixed film anaerobic digester was performed, and while the fixed film system resulted in a considerably smaller digestion tank (45% of the completely mixed tank volume), the cost of the fixed film media, special support and distribution system resulted in an overall higher cost. Therefore, the completely mixed system was selected for the anaerobic digester.

In a completely mixed anaerobic digestion system, actively growing bacteria are displaced from the digester as new feedstock is added to the digestion system each day. A minimum liquid retention time is necessary for the remaining bacteria to grow and replace the displaced bacteria. The growth rate of these bacteria will control the throughput rate of the digestion system. The pilot-scale laboratory studies on swine manure indicated that at retention times of less than 7.5 days, the specific biogas production rate and volatile solids removal efficiency decreased significantly. A minimum theoretical hydraulic retention time of 9.5 days was selected for the full-scale design.

2.1.2 Manure Handling and Digester Feeding System Design

The selection of the manure handling, and digester feeding system is an important consideration that must be evaluated during the design of a farm scale anaerobic digestion facility. Many existing medium to large scale hog operations in Canada are designed to provide manure storage in the barn, usually in the form of a large pit located under a slatted section of the animal pens. The size of these tanks varies from one week to six months of manure storage. The tanks are usually deep, long and rectangular, making mixing of the contents difficult and energy intensive. Swine manure separates very quickly upon standing into three distinct phases, a sedimented component or sludge in the bottom of the tank, a suspended slurry in the center of the tank and a surface crust. If the manure is pumped from the tank without adequate mixing, the volatile solids concentration will vary considerably from day-to-day, and the biogas production becomes irregular and the digester operation becomes unreliable.

Linden Lee Farms swine housing facilities consist of two barns, a starter barn holding about 400 animals from 15 to 40 kg, and a finishing barn holding about 1000 animals from 40 to 100 kg.

The Linden Lee Farms finishing barn is a partially slatted floor, shallow manure pit barn. The manure flows by gravity to a holding tank located at one end of the barn.

The starter barn is a combination of stable cleaner and hand scrapping to a gutter. The liquid from the starter barn flows by gravity to a holding tank located at the end of the barn. The manure solids are scrapped into a stable cleaner and deposited in the holding tank with the liquids.

Periodically, the tank is mixed and pumped to the holding tank in the finishing barn.

The manure from a nearby poultry and swine farm is also spread on Linden Lee land. A pipeline from the neighbouring farm was designed and installed, and the poultry manure and some of the swine manure from this operation is periodically pumped to the holding tank located in the finishing barn.

2.1.3 Electrical Generation System Design

The sizing of the electrical generation system (or any biogas utilization system) is critical to the operation of the overall system. If the electrical generation system is oversized, inefficient use of the biogas will result in a very low economic return.

Inadequate biogas storage may result in the electrical system running out of biogas during peak power demands, significantly reducing the economic return or causing considerable inconvenience to the operator.

Undersizing the unit will result in significant quantities of biogas being wasted while power is being purchased from the grid reducing the economic return from the system.

The initial biogas production estimates indicated that even if all the manure were used from both farms, the electrical generation potential of the system would fall short of supplying all the electrical power to the farm at peak times of the day. Generation capacity at other times of the day would exceed the farm requirements and excess power would be available. Since the cost of biogas storage for high demand periods is extremely expensive, it was decided to sell this excess power to the grid.

Two alternatives are available to import and export power to the grid as follows:

Alternative 1 - Self Excitation Generation and Switch-Gear System

A self excitation generator, very similar to the type used for standby power, must have a source of DC power to excite the field windings of the generation system. There must be controls to apply this field at just the right time, to monitor and adjust the field current and voltage and to protect the machine against "loss of field" and overheating. The output frequency from this generator is a function of the number of field poles and the

rotational speed of the armature. To synchronize this power to the grid requires a frequency sensor on the grid, a compartitor is required to compare the grid frequency to the generator frequency and to provide a control signal to the engine to adjust the armature speed. A reverse power relay switch is also required to isolate the generator from the grid in the event that the power on the grid is shut off. The cost of this equipment is prohibitive for small generation systems and was not considered for the Linden Lee system.

Alternative 2 - Induction Generation with an Import/Export System

An induction generator receives its excitation power from the utility grid and is always synchronized. An increase in the speed of the prime mover (engine) once above the synchronization speed, will increase the power output of the generator up to the maximum output. Since engine speed governs power output from the generator, a load sensor and import/export system are required to regulate the generator output. The Import/Export system allows the operator to minimize the power purchased from the grid. The import module can be set to import a specified percentage of power from the grid if the biogas production is low. The export module can be set to export power to the grid if the biogas production is high. In the normal operation mode, any level of imported or exported power can be set by the operator.

The cost of power from Maritime Electric includes the cost of purchase and transmission of the power to the user. Maritime Electric is expected to maintain and service the transmitting equipment for the power export at Linden Lee Farms, so a buy back rate of approximately $0.045 to $0.055 was estimated.

The decision was made to purchase an induction type generator with the Import/Export system. This system appeared to provide the most flexibility and the minimum cost.

Table 1 summarizes the design statistics for the Linden Lee Farms Anaerobic Digestion and Electrical Co-generation System.

2.2 Facility Description

A schematic of the Linden Lee Farms Anaerobic Digestion and Electrical Co-Generation System is shown in Figure 1. The system consists of a

TABLE 1. SUMMARY OF THE LINDEN LEE ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM DESIGN PARAMETERS

Manure Characteristics		
Volume (m^3/d)	30	
Dry Matter (%)	6	
Volatile Matter (%)	5	
Digester Design		
Active Volume (m^3)	285	
Gas Storage (m^3)	45	
Operating Temperature (°C)	35	
Hydraulic Retention Time (days)	9.5	minimum
Maximum Organic Loading (kg VS/d)	4.5	maximum
Gas Handling		
Biogas Blower Capacity (m^3/d)	735	maximum
Additional Biogas Storage Volume (m^3)	23	
Effective Storage Volume (m^3) *	9	
Biogas Storage Pressure (kPa)	40	
Electrical Generation		
Maximum Generating Capacity (kW)	40	
Average Power Production (kW-hr/d)	350	
Biogas Utilization Efficiency (kJ/kW)	13,200	
Heat Recovery System		
Engine Water Jacket (GJ/d)	1.68	average
Exhaust Gas (GJ/d)	1.44	average
Radiant Heat (GJ/d)	0.38	average
Total Excess Usable Heat (GJ/d)	1.71	average

* The additional biogas storage consists of a steel tank and the effective storage available is due to gas compression only.

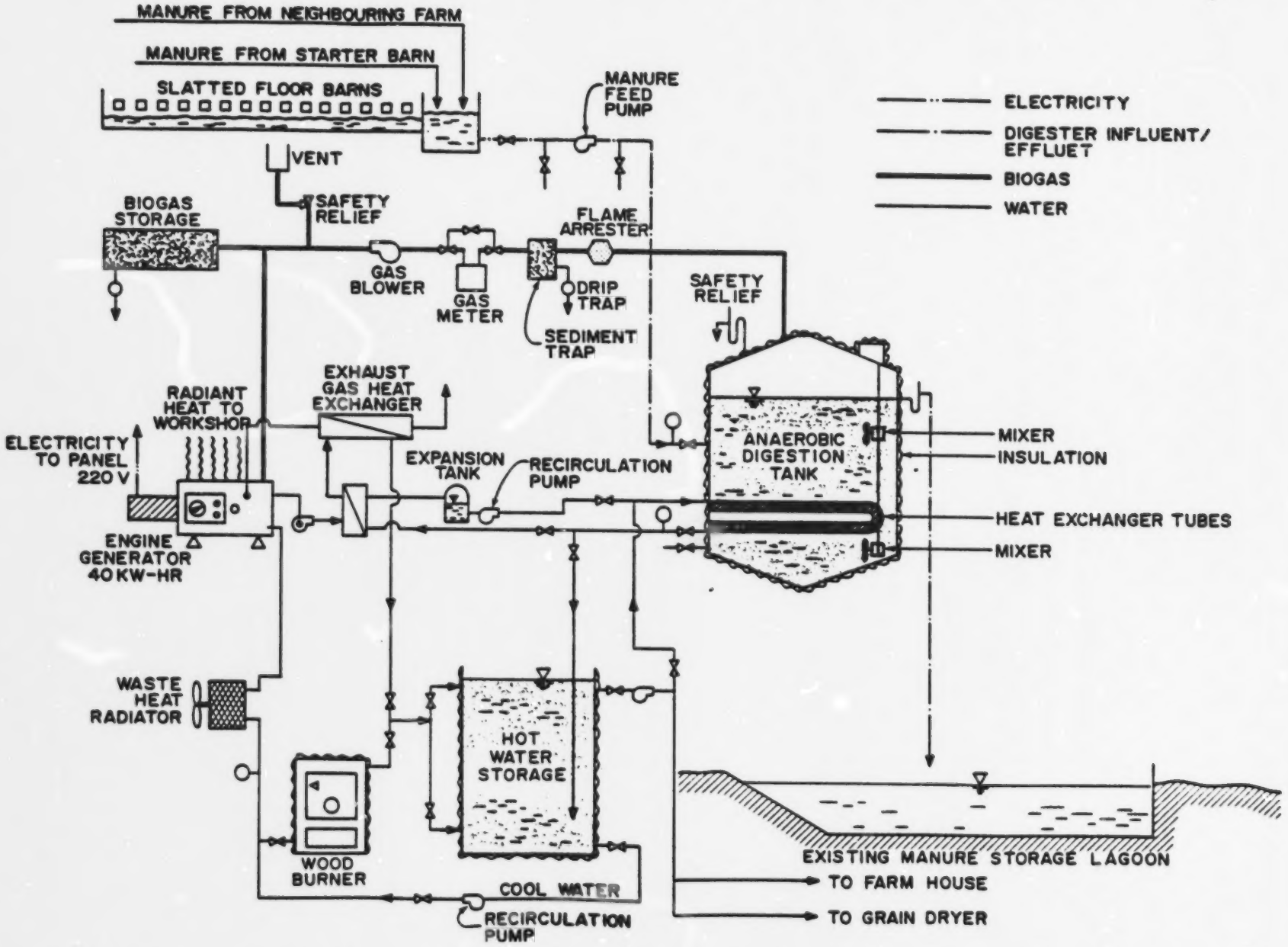


FIGURE 1 — SCHEMATIC OF THE LINDEN LEE FARMS ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM

6.6 meter diameter by 6.6 meter high, totally enclosed, circular reinforced concrete tank. The tank is insulated with 5 centimeters of Urethane foam insulation covered with a UV barrier top coat. The digester contents are continuously mixed with two submersible style low energy mixers, one located near the bottom of the digester running continuously, and the other one operating near the surface to break up any scum formation.

Manure from the finishing barn, starter barn and neighbouring poultry and swine farm is pumped once daily to the digestion tank using the manure transfer pump. The digested liquid overflows through a gas/liquid trap assembly located on the digester to a nearby storage tank and lagoon.

The biogas is withdrawn from the digestion tank and directed through a flame arrester, sediment trap, gas meter and gas blower to a 23 cubic meter low pressure biogas storage tank. The storage tank acts as a buffer between daily gas production and daily use.

The biogas is used, without scrubbing, to fuel a 55 kW natural gas engine and drive a 40 kW electrical generator. This electrical power is used to displace purchased power to the farm.

The heat from the engine cooling system and from an exhaust gas heat exchanger is recovered and used to heat the farm house, and the digestion system. Radiant heat from the engine is used to heat the workshop.

The relatively odour free liquid remaining after anaerobic digestion flows by gravity to an earthen storage lagoon and is used as fertilizer on the farm land.

2.3 Construction

2.3.1 Digestion Tank Construction

Construction of the digestion tank was initiated in June, 1983. The excavation for the tank was complete and the bottom carefully graded to the angle of the floor. The circumference of the tank was formed to provide the footings. The bottom of the excavation was lined with coarse sand and five (5) centimeters of Styrofoam SM insulation. The reinforcing steel was placed, and the floor and footings poured in one pour using premixed concrete. The footings were allowed to cure for approximately two days before the wall construction was started.

The walls were constructed using movable steel forms. A special forming rig was mounted in the center of the tank and was used to hold and raise the forms, and provide a scaffold for the construction crew.

The forms are designed to pour one ring of concrete around the circumference of the tank 122 centimeters high. After the concrete cures for twenty-four hours, the steel forms are removed and moved up to the next ring. The walls of the tank are constructed by repeatedly moving the forms from the wall section previously poured, placing them on top of the poured wall, and pouring the next ring.

As the wall construction progressed, specially designed fittings were placed at the appropriate positions in the walls to provide the influent, effluent, and heat exchange inlets and outlets for the digestion system. Extra wide water stops were placed in the wall section to ensure a gas tight seal between the wall and the roof.

The forming rig used for the tank wall construction was used to form a conical roof for the digestion tank. The roof forming system required a 60 centimeter center manhole to secure the reinforcing bars. A second manhole for the mixing system and general tank access was provided.

A special 10 centimeter biogas outlet was formed into the roof approximately half way to the center of the conical roof section.

The roof was poured in a single pour. After the concrete cured for approximately 48 hours, the forms and forming rig were removed through the manhole.

The tank below grade was insulated by placing 61 centimeter by 244 centimeter sheets of Styrofoam SM, 5 centimeters thick around the tank circumference. The walls above grade were spray insulated with a concrete sealer, 5 cm of polyurethane foam and two applications of protective top coat.

The concrete was allowed to cure for 90 days before putting manure in the tank. A photograph of the completed digestion tank is shown in Photograph 1.

2.3.2 Digester Heat Exchanger

The digester heat exchange system consists of approximately 110 meters of 5 cm diameter low carbon steel pipe located in five loops, in series, approximately 0.2, 0.4, 0.6, 0.8 and 1.0 meters off the bottom of the digestion tank, and approximately 0.5 meters from the digester exterior wall.

PHOTOGRAPH 1: COMPLETED ANAEROBIC DIGESTION TANK AND CONTROL BUILDING

2.3.3 Digester Mixing System

The digester mixing system consists of two (2) submersible mixers mounted on a single mast. The lower mixer is located approximately 1 meter off the bottom of the digester. The second mixer is located about 0.6 meters below the digester liquid surface level.

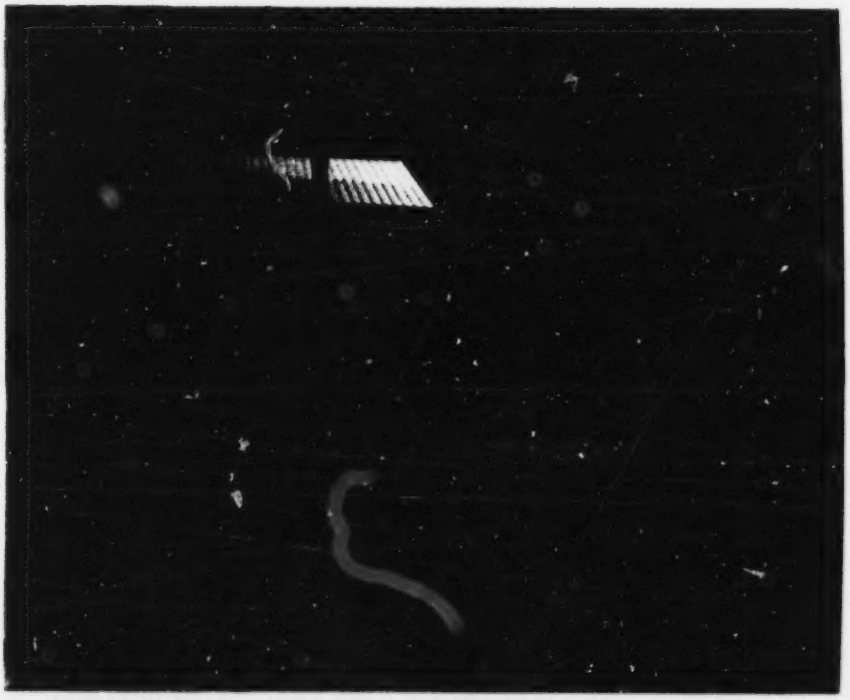
2.3.4 Biogas Handling and Storage System

The gas handling system consists of a flame arrester, sediment/moisture trap, biogas flow meter and a rotary lobe biogas blower. Photograph 2 shows part of the biogas train.

A 23 cubic meter steel biogas storage tank proved to be the most economical form of biogas storage. Several coats of rust resistant paint were applied by hand to the exterior of the biogas storage tank for protection from corrosion. A condensate removal line was placed in the biogas storage tank. The tank is located behind the workshop near the engine generator set, as shown in Photograph 3.

When the biogas storage tank is full (40 kPa), a pressure relief valve vents the excess gas to a vent stack mounted on the side of the

PHOTOGRAPH 2: BIOGAS TRAIN SHOWING THE FLAME ARRESTER, SEDIMENT TRAP AND PRESSURE SWITCHES



PHOTOGRAPH 3: WORK SHOP AND BIOGAS STORAGE TANK

digester control building. The vent stack extends 1 to 2 meters above the peak of the building roof.

2.3.5 Digester Control Building

A digester control building was constructed to house the gas handling and safety equipment. The digestion tank wall forms one wall of the building and all the connections to the interior of the digester with the exception of the biogas line, manure and effluent lines are accessible through the building.

The building is approximately 2 m by 2 m and is of frame construction with coloured metal siding on a poured concrete foundation and a gravel floor. All of the piping, with the exception of the biogas lines, were brought into the building below grade.

2.3.6 Electrical Generation System

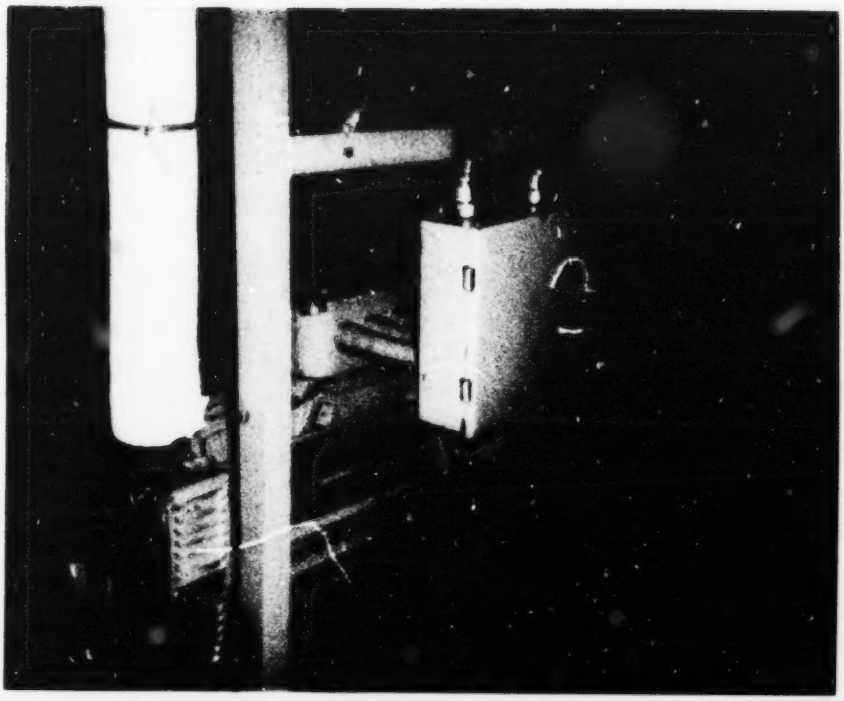
The electrical generation system consists of a 6 cylinder natural gas fueled internal combustion engine, a 40 kW induction 220 V - single phase generator, an engine water jacket heat recovery system and an engine exhaust gas heat recovery system. A side view of the engine generator system is shown in Photograph 4, and a front view of the control panel is shown in Photograph 5.

The engine was designed to operate on both propane and biogas. It will automatically switch from biogas to propane if the biogas pressure should drop and automatically return to biogas when the biogas pressure is restored.

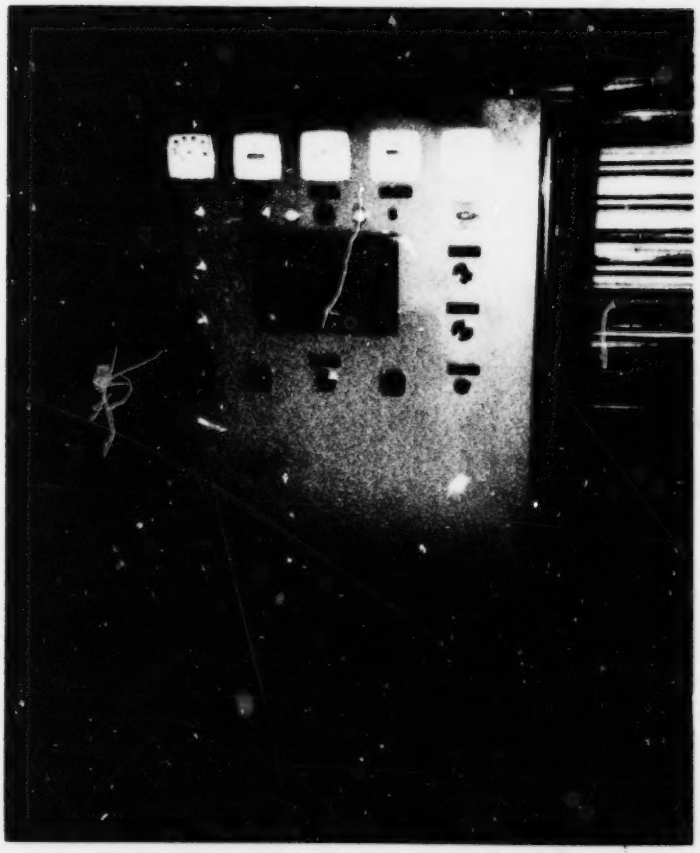
The engine is equipped with a biogas pressure reduction valve to reduce the biogas pressure from the storage pressure of up to 40 kPa to the 3.5 kPa required by the low energy fuel carborator.

The engine is equipped with two (2) over temperature shut downs, an over speed and a low oil pressure shutdown.

The biogas and propane fuel supply lines automatically close if any of the shutdowns are tripped.

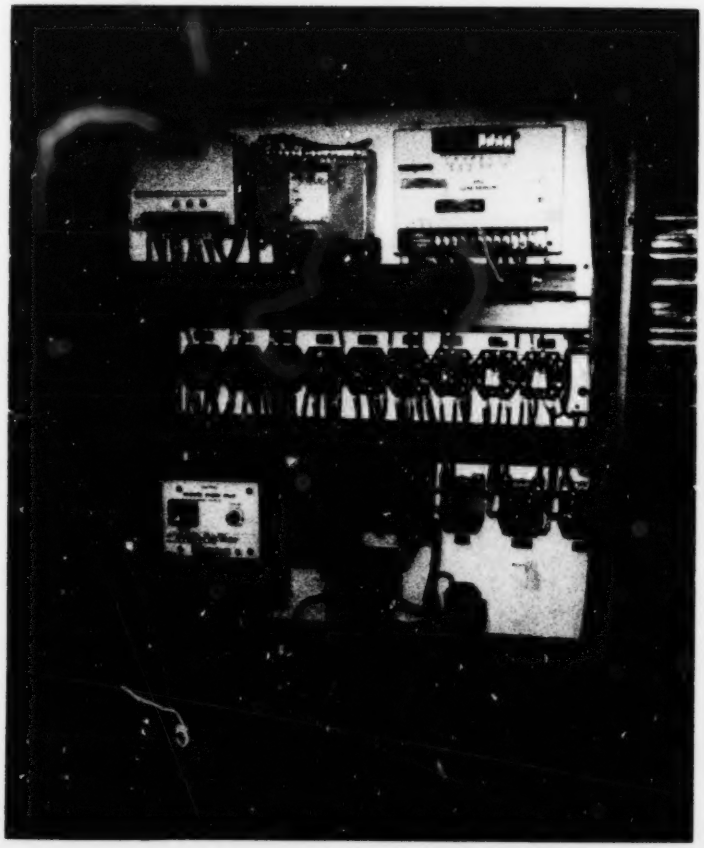


PHOTOGRAPH 4: ENGINE GENERATOR SYSTEM



PHOTOGRAPH 5: MAIN CONTROL PANEL ON THE ENGINE-GENERATOR SYSTEM

The electrical control system consists of a load sensing module, Import/Export module and a reverse power relay module as shown in Photograph 6.



PHOTOGRAPH 6: MAIN ENGINE-GENERATOR CONTROL PANEL INCLUDING THE LOAD SENSING, IMPORT/EXPORT AND REVERSE POWER MODULES

When the engine is started, the engine governor brings the engine to the synchronization speed of the generator and then maintains this speed until it is synchronized with the grid. When synchronization is achieved, the main contact relay closes and the induction generator field is excited and starts to produce power. Photograph 7 shows the main contact relays and the power grid connection to the engine generator.

The import/export module controls the total power generated by the generator in the following manner:

PHOTOGRAPH 7: MAIN CONTACT RELAYS AND POWER GRID CONNECTIONS

(1) If the import is set to zero, all power for the farm is generated by the generator up to its capacity. When the generator capacity is exceeded, the remaining required power is imported from the grid.

(2) If the import module is not set to zero, then a percentage of the power required by the farm is imported (i.e. if the import setting is at 50%, then 50% of the farm power will be supplied by the generator and 50% will be supplied by the grid).

(3) If the export module is set to zero, no power will be exported to the grid.

(4) If the export module is not set to zero, then a percentage of the generated power will be exported (i.e. if the export setting is set

and export 20% more power to the grid). If the farm demand exceeds the generator capacity then the exported power will be reduced as required.

The reverse power relay is provided as a safety feature. If the grid power is shut down, the reverse power relay will sense the loss of power and disconnect the engine generator from the grid until the power on the grid is returned. This protects people working on the power line from electrical shock in the event that the generator exports power.

The induction generator is also equipped with a capacitance bank. The capacitors provide a small reserve of power that can be used to excite the generator in the event that no excitation power is available from the grid. This gives the generation system a standby capability when the grid power is off.

2.3.7 Heat Recovery System

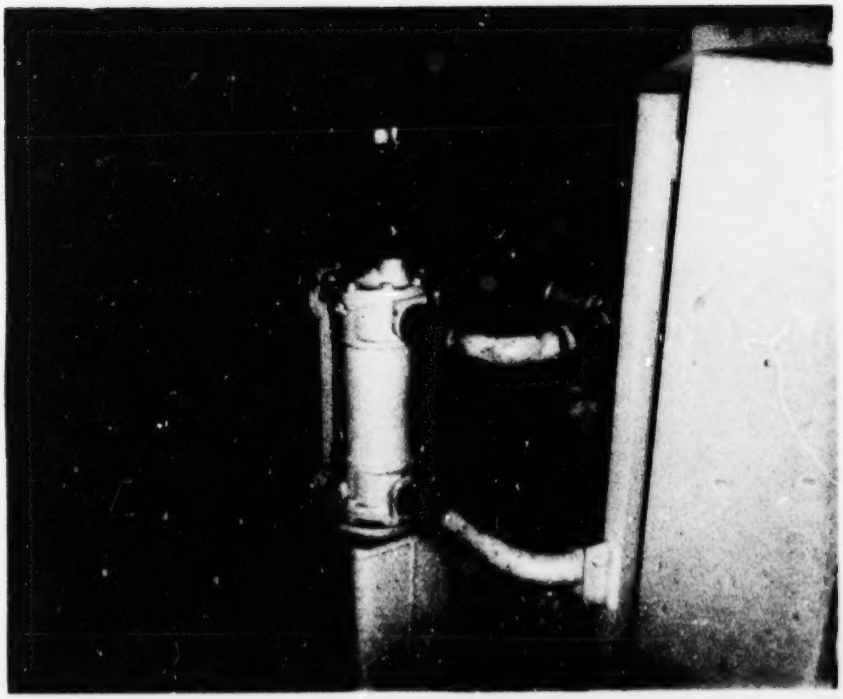
The engine heat recovery system consists of two complete and separate cooling water circuits.

The primary engine cooling circuit consists of a water-to-water shell and tube heat exchanger, a coolant expansion tank, a recirculation pump and the digester heating coils. The water-to-water heat exchanger is shown in Photograph 8.

The coolant in this circuit is pumped through the engine heat exchanger where it gains heat from the engine. The coolant flows to the coolant expansion tank to release any entrapped air and/or to expand as the coolant heats up. The suction side of the recirculation pump is connected to the bottom outlet of the expansion tank and the coolant is pumped through the digester heating coils and then returns to the engine heat exchanger. The flowrate through this loop regulates the temperature between 45°C and 55°C.

The engine operating temperature is regulated at 85°C by a thermostat located in the engine block.

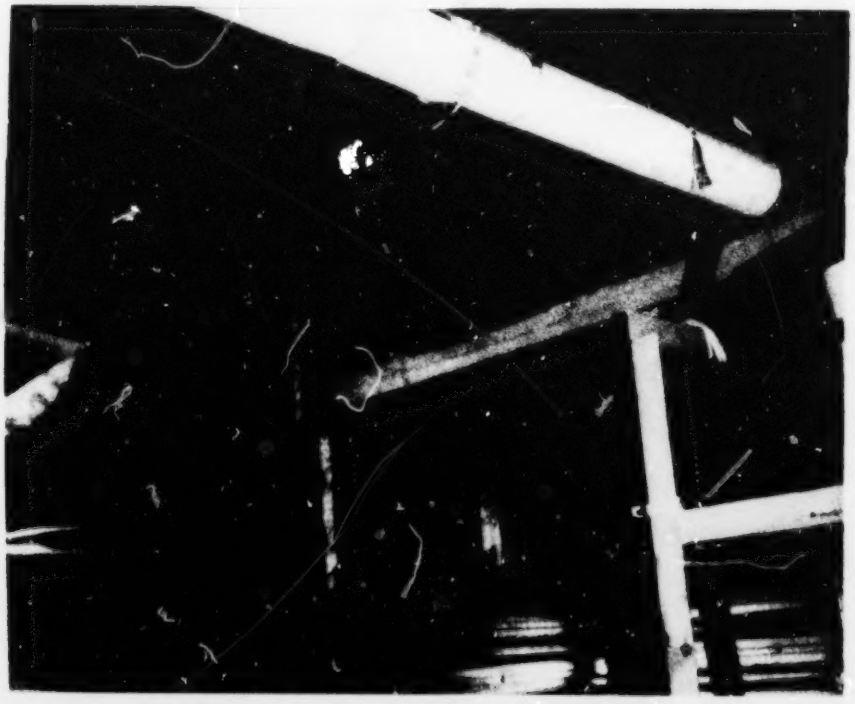
A second heating loop consists of the engine recirculation pump, an exhaust manifold heat exchanger, an exhaust gas to water heat exchanger, a 27 m^3 hot water storage tank and a waste heat radiator.



PHOTOGRAPH 8: HEAT RECOVERY SYSTEM, WATER-TO-WATER HEAT EXCHANGER (foreground) AND WATER-TO-EXHAUST GAS HEAT EXCHANGER (background)

The waste heat radiator is connected in the cool water return from the hot water storage tank as shown in Photograph 9. A temperature sensor turns on the waste heat radiator fan if the cool water return temperature exceeds 75°C.

The hot water storage tank is connected to the hot water heating system in the house and to a hot water radiator in the grain dryer. Hot water from this tank is circulated as required through the house and grain dryer.



PHOTOGRAPH 9: WASTE HEAT RADIATOR

2.4 Digestion Process Start-Up

On January 20, 1984, the digestion system was started. Since no anaerobic digestion systems were operating on the island at the time of start-up (the municipal digester was being repaired), and the cost of bringing seed in from the mainland was prohibitive, the digester was started without seed material. The digester was filled with raw manure from the barn over a period of several weeks, while the work on the electrical generation system was completed.

Sampling was initiated March 6, 1984. At the initiation of sampling, the total volatile acids/bicarbonate alkalinity ratio was observed to be extremely high, 3.7 compared with normal operational levels of 0.3 to 0.6. Feeding of the digester was suspended immediately and no manure was added to the digester for almost six weeks while bacterial seed developed and acclimatized to the swine manure. When the total volatile acid/bicarbonate alkalinity (VA/BA) ratio started to drop, feeding of manure was resumed at 25% to 30% of the design volumetric loading rate.

On April 18, 1984, a fire burnt the workshop down and severely damaged the engine generator system. The unit was removed and returned to

Toronto, Ontario for rebuilding. The generator was not returned to Linden Lee Farms until September, 1984.

During the time the generator was being rebuilt, the digester was operating under relatively steady conditions using the the wood and straw burner as a source of heat. Monitoring of the digester was suspended until August 1, 1984.

2.5 Facility Operational Schedule

The digestion system operational schedule was developed over a period of several months by trial and error. The schedule that appears to be the most convenient to the farm personnel and still provides stable digester operation is as follows. The manure from the starter barn and the neighbouring swine and poultry farm is pumped to a holding tank located in the swine finishing barn once each week. The contents of this tank are mixed using the manure pump and then pumped to the digester tank on a batch basis once each day. The volume of manure pumped to the digester is estimated by measuring the manure depth in the tank at the start of pumping and then observing the change in depth until a pre-determined depth is reached. The manure tank holds approximately 400 litres of manure per centimeter of depth.

The final effluent from the digester is displaced by the incoming manure and flows through a water trap assembly on the outlet of the digester to a final storage lagoon.

The biogas blower operates as required on a pressure switch and fills the biogas storage tank and/or provides fuel to the generator system.

The generator system automatically starts up and generates when the biogas pressure reaches 28 to 35 kPa in the biogas storage tank and shuts down automatically when the biogas pressure is lowered to 7-10 kPa.

Hot water from the heat recovery system is supplied to the anaerobic digester tank as required by a thermostatically controlled recirculation pump. The remaining heat from the engine is discharged to the existing 27 m^3 hot water storage tank. If the engine return water becomes to hot, a thermostatically controlled fan and radiator system wastes heat from the hot water storage tank to the workshop.

3.0 PERFORMANCE MONITORING

3.1 Digestion System Monitoring Program

The performance monitoring program was continued on August 1, 1984 following completion of the repairs to the engine generator system. The monitoring program lasted for 7 months ending on February 28, 1985.

Once a day, samples of the digester influent (i.e. raw manure) and effluent (i.e. digested manure) were grabbed and added to a weekly composite stored in an on-site refrigerator. These composite samples were shipped to CANVIRO's analytical laboratory located in Kitchener, Ontario where they were analyzed for Total Solids (TS), Total Volatile Solids (VS), Total Kjeldahl Nitrogen (TKN), Ammonia Nitrogen (NH_3) and pH.

A sample of the biogas produced was also shipped to the laboratory and analyzed for Methane, Carbon Dioxide, Carbon Monoxide, Oxygen and Nitrogen.

Readings from the biogas meter, total farm electrical power meter, engine generator power meter, imported power meter and exported power meter were made each day. The Digester operating temperature and engine operating temperature were also recorded daily.

3.2 Digestion System Monitoring

Table 2 summarizes the average digester influent and effluent characteristics over the duration of the monitoring program.

TABLE 2. SUMMARY OF THE DIGESTER INFLUENT AND EFFLUENT CHARACTERISTICS

PARAMETER	DIGESTER INFLUENT		DIGESTER EFFLUENT		% REMOVAL
	MEAN	SD *	MEAN	SD	
pH	6.7	0.22	7.8	0.16	-
Total Solids (%)	3.53	1.14	2.36	0.47	33.1
Volatile Solids (%)	2.42	0.86	1.50	0.39	38.0
Volatile Solids (% of TS)	68.06	3.97	63.39	3.79	6.0
TKN (mg/L)	3816	627	3802	339	0.4
NH_3-N (mg/L)	2736	439	3133	290	-14.5

* standard deviation

The pH of the influent averaged 6.7 and the effluent averaged 7.8. This increase in pH is a result of an equilibrium formed between the acid and methane forming bacteria present in the digester.

The total residual solids were reduced from 3.53 percent in the digester influent to 2.36 percent in the effluent corresponding to an average removal of 33 percent.

The volatile solids in the influent averaged 2.42 percent and the average volatile solids in the digester effluent was 1.50 percent. The average volatile solids removal across the digester was 38 percent.

The volatile solids in the digester influent averaged 68 percent of the total solids and the effluent averaged 63 percent. This corresponds to an average reduction of 6.0 percent of the volatile solids across the anaerobic digester.

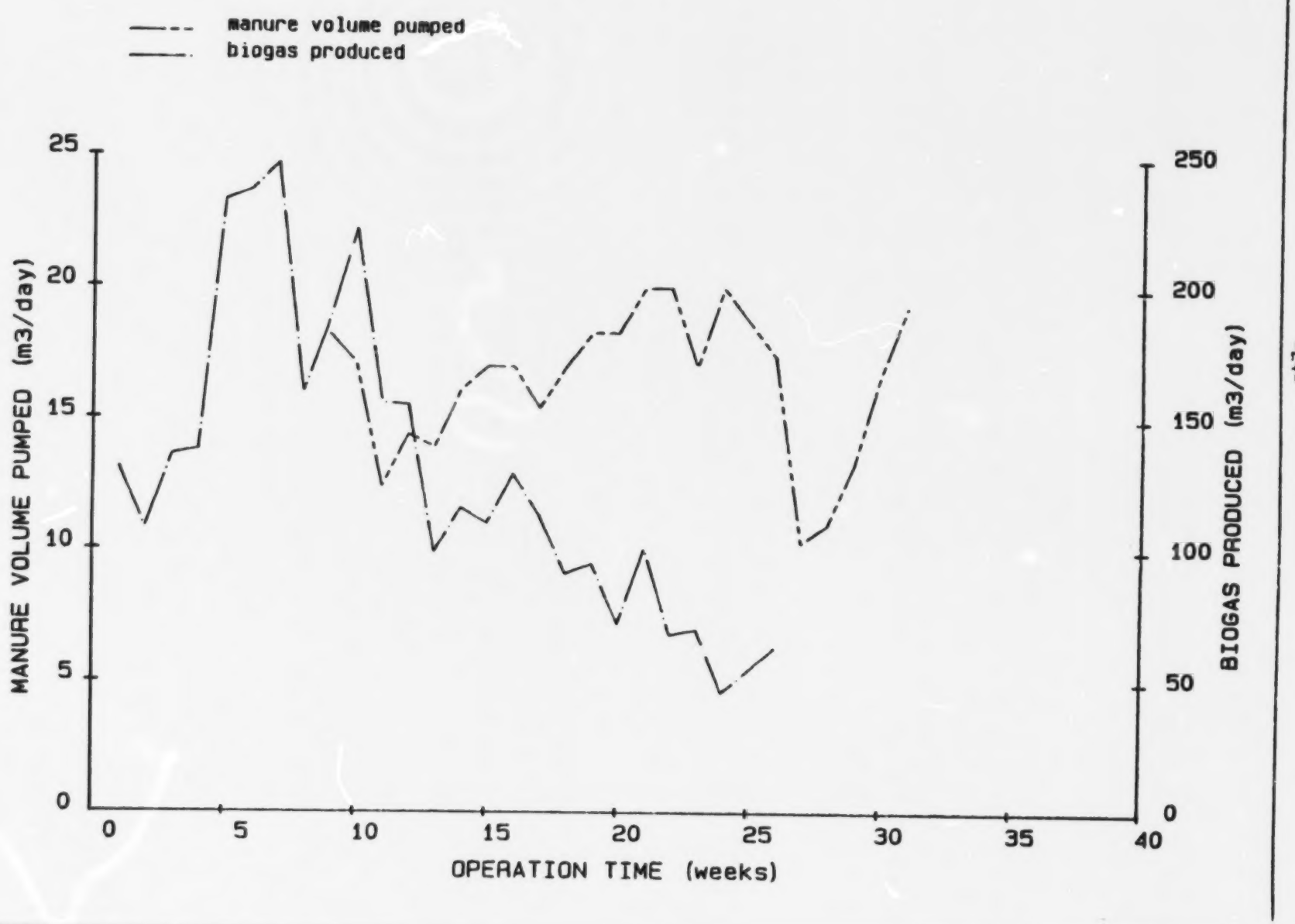
The total Kjeldahl nitrogen (TKN) remained unchanged throughout the digestion process with an average removal of less than one percent. The total Kjeldahl nitrogen content of the digester influent averaged 3816 mg/L and the digester effluent averaged 3802 mg/L. The ammonia nitrogen (NH_3-N) content increased, as a result of anaerobic digestion, from 2736 mg/L in the influent to 3144 mg/L in the effluent. This is equivalent to an average increase in the ammonia nitrogen content of 14 percent.

Figures 2 through 6 summarize the digester influent and effluent characteristics for the composite samples collected each week of the monitoring program.

Figure 2 summarizes the daily manure volume pumped and the daily biogas produced. The data presented are the average levels for each week of operation. Manure was being processed from approximately 1400 head of finishing hogs at the Linden Lee home farm combined with the manure from the neighbouring poultry and swine farm. The manure collection system at the neighbouring farm consists of runoff from several manure piles and from the livestock housing units and no estimate of the number of contributing animals was possible. The average manure volume pumped to the digester during the monitoring program was 16 m^3/day and ranged from 10 to 20 m^3/day.

When the monitoring program was resumed on August 1, 1984, a backlog of manure was available from the neighbouring farm. During the first 10 weeks of the monitoring program, manure was processed through the digester at a level greater than the level of manure production, and the biogas produc-

FIGURE 2. SUMMARY OF THE MANURE VOLUME PUMPED AND BIOGAS PRODUCED LINDEN LEE FARMS 1984 - 1985.



tion level was quite high, averaging 180 m^3/day. As less manure was available to feed to the digester, the biogas production decreased.

Near the end of the monitoring program, condensation and corrosion of the gas meter caused inaccurate biogas readings. During week 27 of the monitoring program, the biogas meter failed completely and was removed from the gas train.

Figures 3 and 4 summarize the total solids and volatile solids in the digester influent and effluent respectively. The high variability measured in the total solids content of the digester influent (i.e. a standard deviation of 1.14 on an average value of 3.53) may be a result of the variability in the manure from the two farms (Linden Lee and neighbour). The digester effluent total solids and volatile solids concentration remained consistent during the monitoring program.

Figures 5 and 6 summarize the total Kjeldahl nitrogen and ammonia nitrogen concentrations in the digester influent and digester effluent respectively. The total Kjeldahl nitrogen concentration in the digester effluent was consistent during the monitoring period. The fluctuations in the influent total Kjeldahl nitrogen corresponded to those in the influent total solids and are likely a result of varying amounts of leaking and clean-up water diluting the manure.

The digester performance is summarized in Table 3 and Figures 7 through 9.

TABLE 3. SUMMARY OF THE DIGESTER PERFORMANCE

PARAMETER	MEAN	SD *
Manure Volume Pumped (m^3/d)	16.18	3.47
Digester Loading (kg VS/d)	386	167
Digester Loading Rate (kg VS/m^3/d)	1.35	0.59
Hydraulic Retention Time (d)	18	-
Biogas Production (m^3/d)	135	63
Specific Biogas Prod. (m^3/kg VS/d)	0.30	0.15
Methane Content	59.6	2.3

* Standard Deviation

The average hydraulic retention time during the study was 18 days. This is well above the minimum design hydraulic retention time of 9.5 days.

FIGURE 3: SUMMARY OF THE TOTAL RESIDUAL SOLIDS
LINDEN LEE FARMS 1984 - 1985.

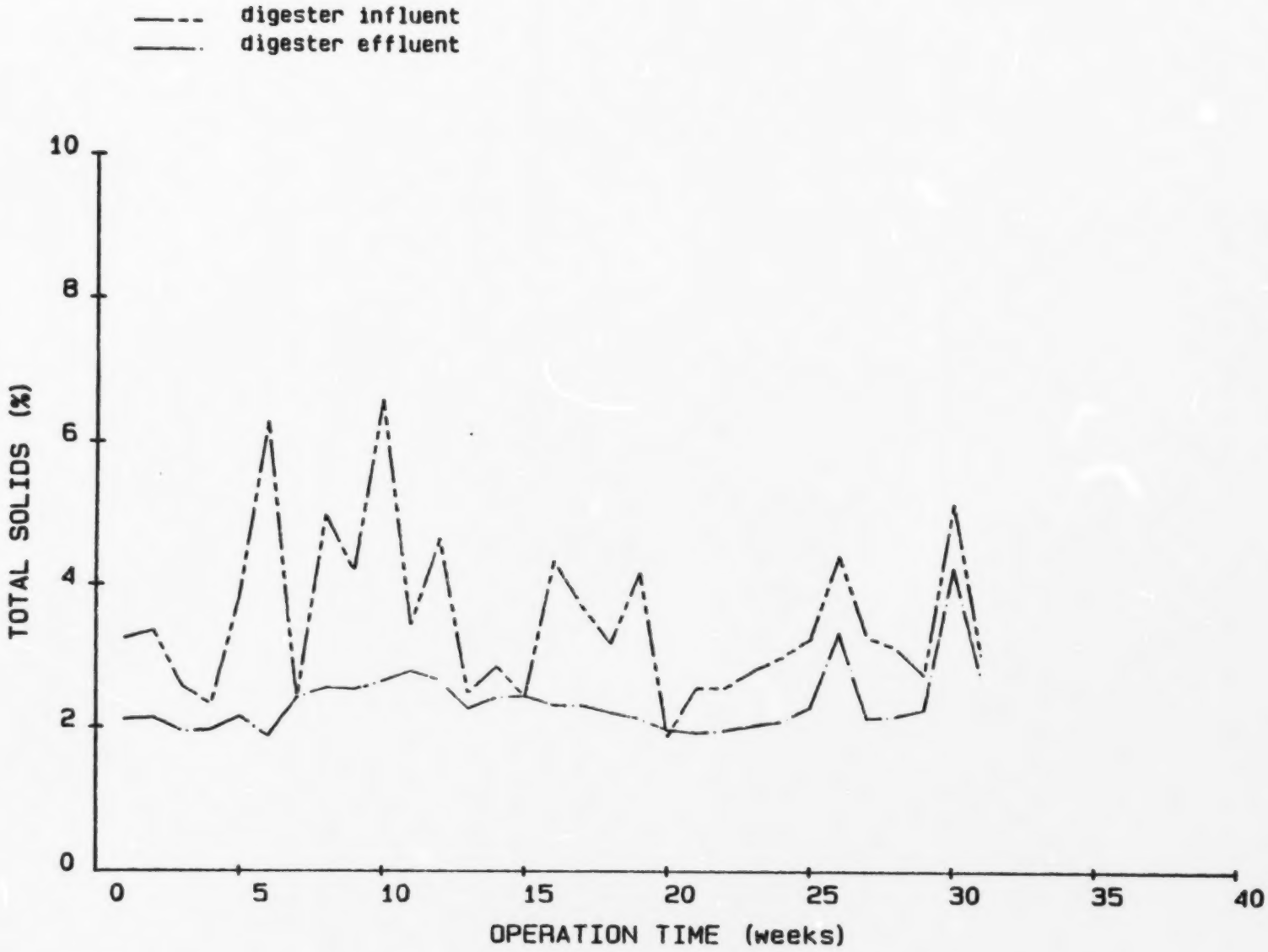


FIGURE 4: SUMMARY OF THE VOLATILE SOLIDS
LINDEN LEE FARMS 1984 - 1985.

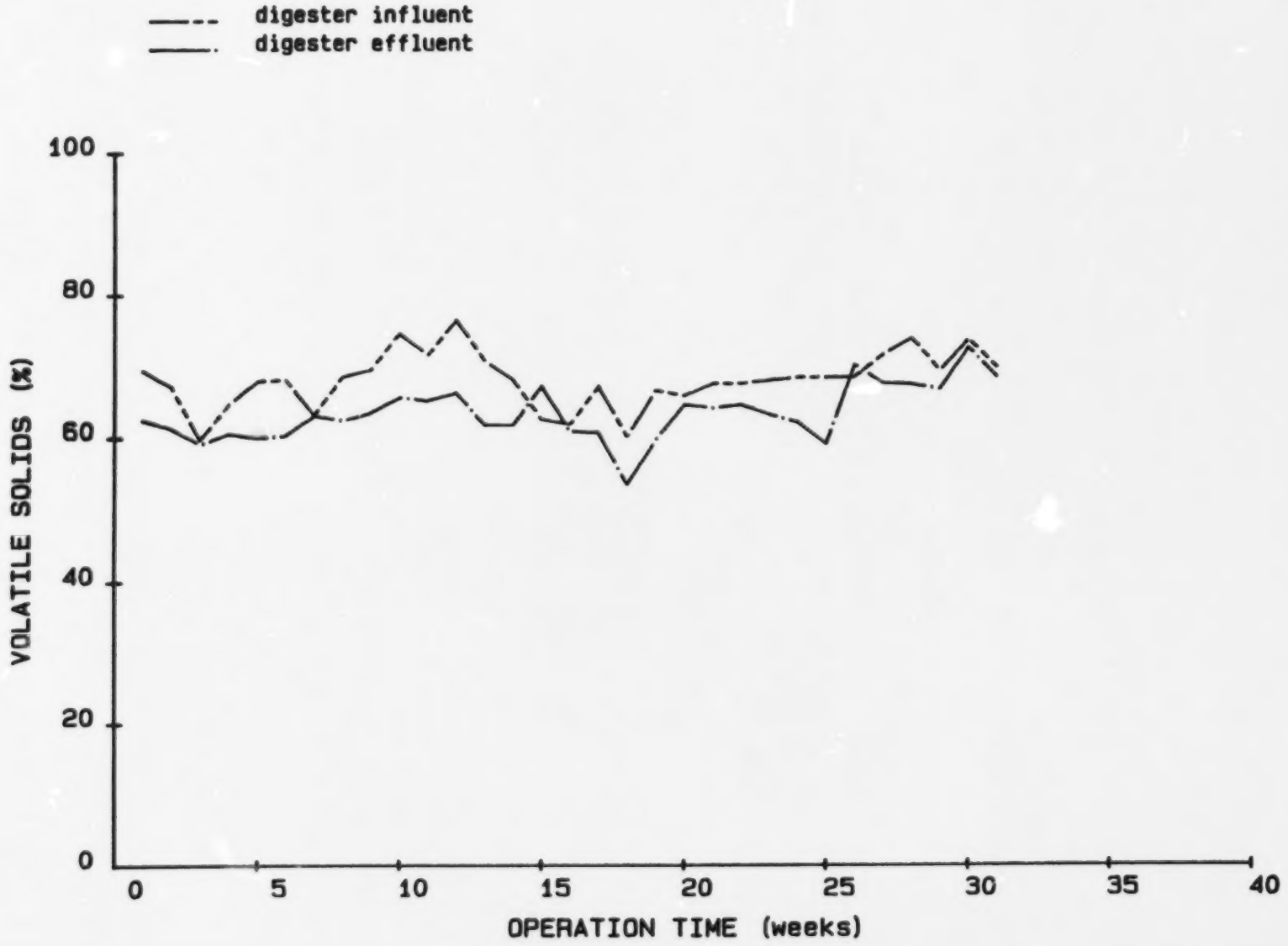


FIGURE 5: SUMMARY OF THE TOTAL KJELDAHL NITROGEN
LINDEN LEE FARMS 1984 - 1985.

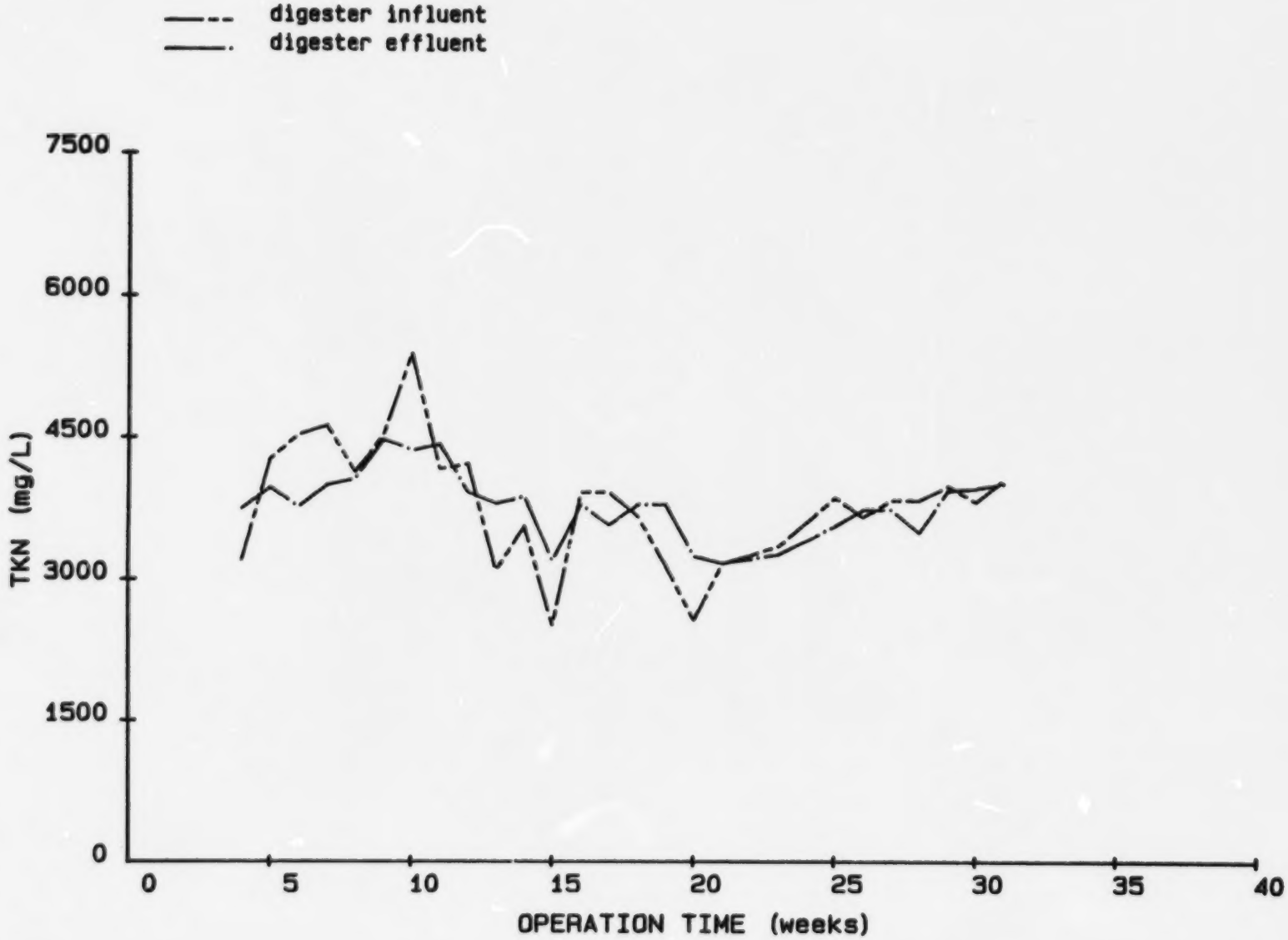
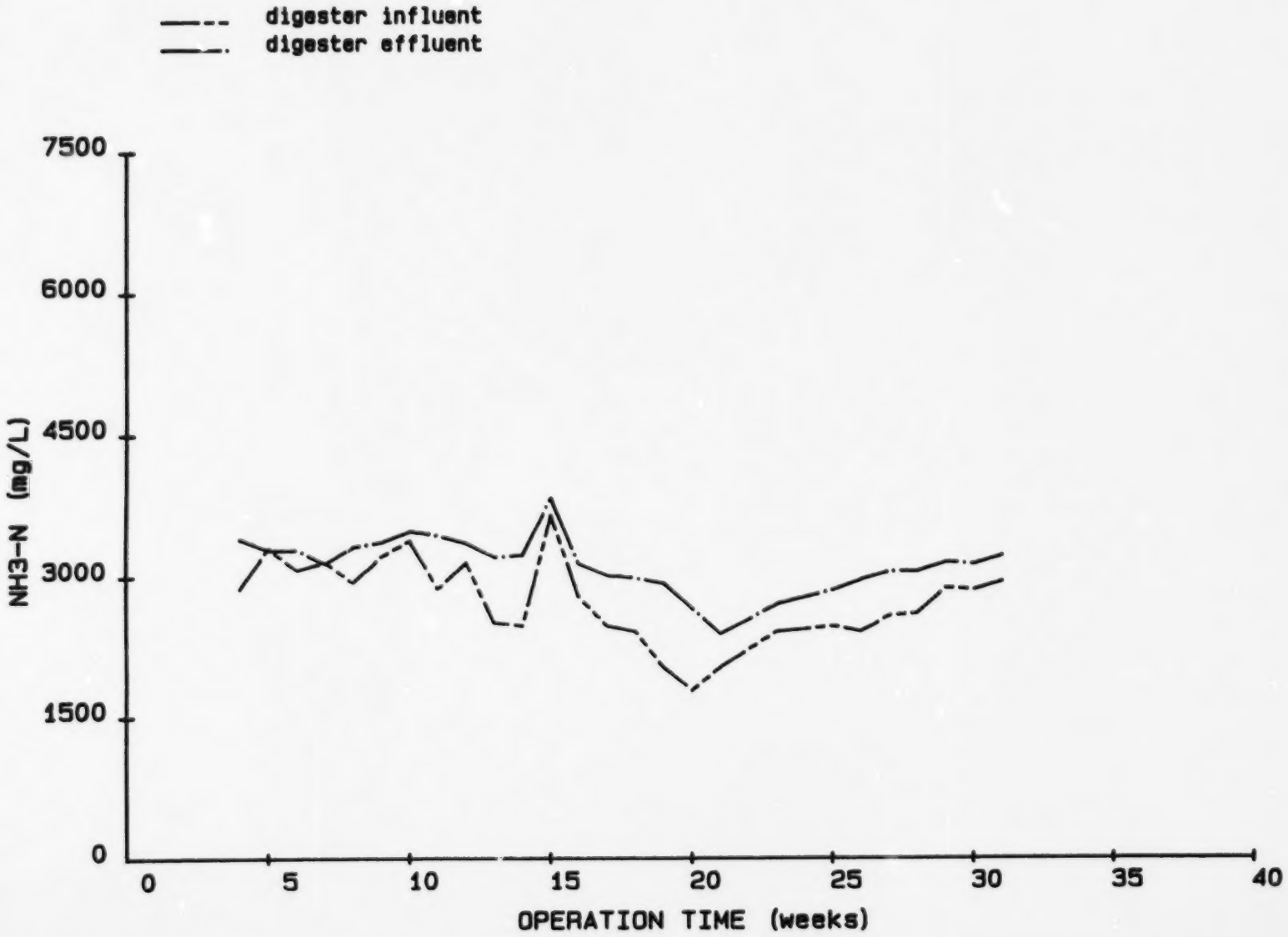


FIGURE 6: SUMMARY OF THE TOTAL AMMONIA NITROGEN
LINDEN LEE FARMS 1984 - 1985.



The pH of the digester influent and the effluent, as summarized in Figure 7, remained constant during the monitoring program with the effluent pH being almost a full pH unit higher than the influent pH.

Figure 8 summarizes the total alkalinity, total volatile acids and total volatile acids/bicarbonate alkalinity ratio measured in the digester effluent each week. The stability of the digestion process may be assessed by the volatile acids/bicarbonate alkalinity (VA/BA) ratio. A ratio of greater than 1.0 indicates the digester is in an upset state and a ratio of less than 0.5 indicates stable digester operation. The maximum VA/BA ratio measured during the monitoring program was 0.23 which indicates operation under very stable conditions. The volatile acids remained below 2000 mg/L during the monitoring program and the total alkalinity remained above 11,000 mg/L indicated an extremely stable digester.

The volatile solids loading to the digester, as summarized in Figure 9, remained consistent throughout the monitoring program, averaging 1.35 kg VS/m^3/day. This is well below the maximum design rate of 4.5 kg VS/m^3/day.

The biogas quality remained consistent at an average of 59.6 percent methane (SD = 2.3) for the duration of the monitoring program.

Specific gas production (Figure 9) calculations were performed using the manure volume pumped, biogas production, and the weekly composite sample analyzed for volatile solids. The specific gas production rate averaged 0.30 m^3/kg VS/day with a standard deviation of 0.15.

The specific biogas production rate determined here is much lower than the 0.7 m^3 of biogas/kg VS fed/day determined at Selves Farms Ltd. (CANVIRO, 1984). The manure collection and handling system at Linden Lee Farms made accurate volatile solids production estimates difficult and may account for the discrepancy between the two systems. The swine rations fed at the two operations are quite different and may account for a difference in the manure digestability. Selves Farms Ltd. feeds a high moisture corn-soybean meal ration while Linden Lee Farms feeds a barley or wheat-soybean meal ration.

3.3 Electrical Generation System Monitoring Program

The electrical generation system monitoring program was initiated November 24, 1984 and continued until February 28, 1985.

FIGURE 7: SUMMARY OF THE pH
LINDEN LEE FARMS 1984 - 1985.

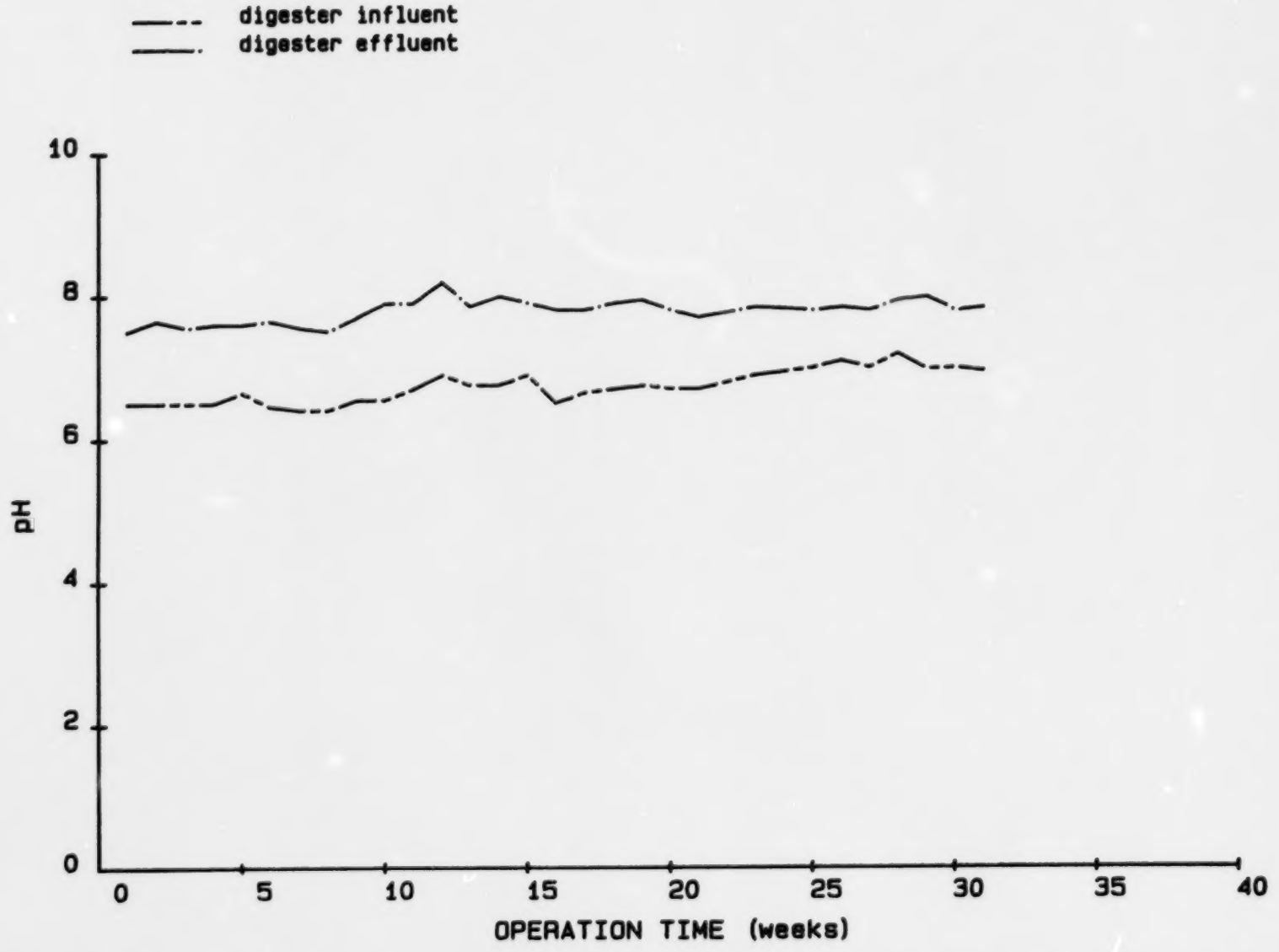


FIGURE 8: SUMMARY OF THE ALKALINITY AND ACIDITY
LINDEN LEE FARMS 1984 - 1985.

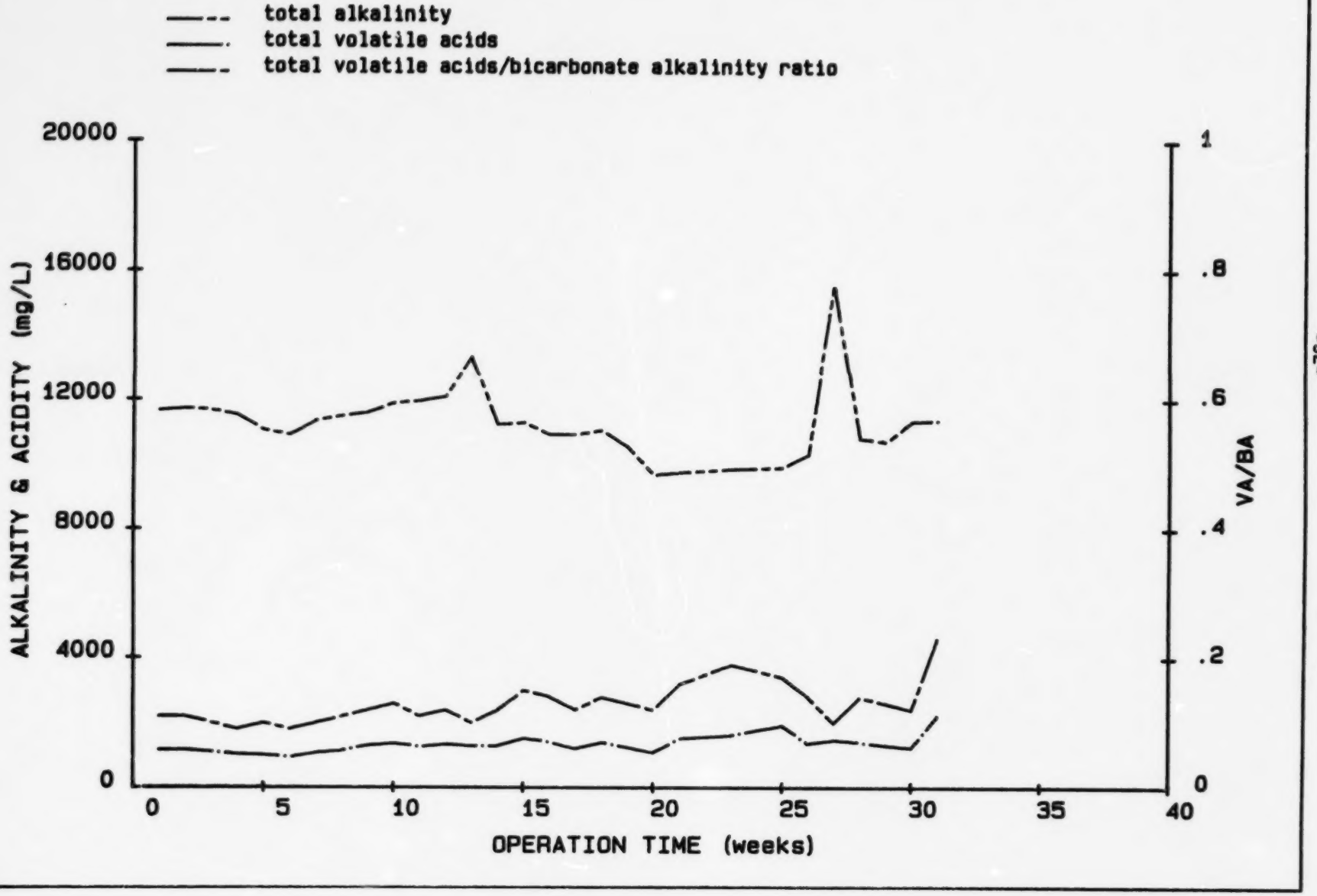
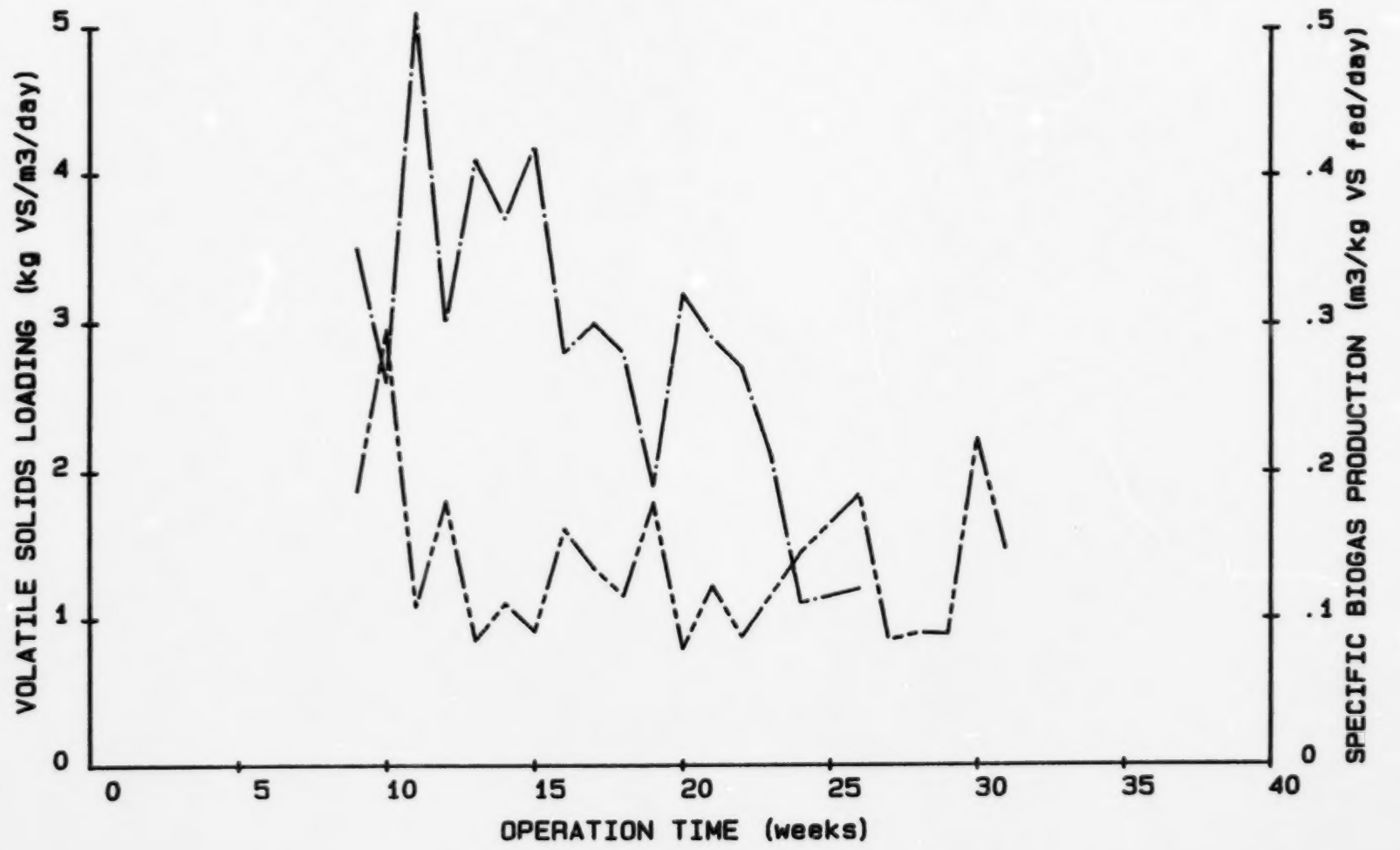


FIGURE 9: SUMMARY OF THE VS LOADING RATE AND BIOGAS PROD. RATE
LINDEN LEE FARMS 1984 - 1985.



Daily readings of electrical power generated, power exported and power imported were taken from various meters installed in the system.

3.4 Electrical Generation System Performance

Table 4 summarizes the average electrical power requirements for Linden Lee Farms during the electrical generation system monitoring period.

TABLE 4. SUMMARY OF THE ELECTRICITY GENERATED

PARAMETER	MEAN	SD **
Electrical Power Production (kW-hr/d)	102	44
Electric Power Exported (kW-hr/d)	11	16
Electric Power Imported (kW-hr/d)	146	48
Total Power (kW-hr/d) *	235	55
Generator Efficiency (kJ/kW-hr)	14,960	5,223

* Total = Produced - Exported + Imported

** Standard Deviation

The electrical power generated by the engine/generator set running on biogas averaged 102 kW-hr/day. The quantity of electrical power exported to the Maritime Electric grid averaging 11 kW-hr/day. The electrical power imported from Maritime Electric averaged 146 kW-hr/day. The total power requirements for the farm, averaged 235 kW-hr/day.

The generator efficiency, expressed as kJ/kW-hr, was calculated by dividing the daily energy equivalent of the biogas consumed by the daily electrical power produced by the generation system. The energy content of the biogas was assumed to be 22,500 kJ/m^3. The average generator efficiency was 14,960 kJ/kW-hr produced.

4.0 DESIGN AND OPERATION PROBLEMS

Manure Production

The biogas (methane) production potential, and therefore the energy production potential of any anaerobic digestion system, is determined by the quantity of biodegradable organic material present in the feed stock. The total organic material in tne feed stock (manure) for most agricultural digestion systems is estimated by determining the total volatile solids concentrations in the manure. The organic loading rate to the digester is expressed as the kilograms of volatile solids fed to the digester each day (kg VS/d).

The specific biogas production rate (or methane) is a measure of the biogas (or methane) produced for each unit of volatile solids processed by the digester each day. The specific biogas production rate provides a method of comparing anaerobic digestion systems operating on the same wastes or comparing the relative degradability of several wastes on the same anaerobic digestion system.

As the retention time of a completely mixed anaerobic digester is lowered, a point is reached when the bacterial growth rate falls below the rate of bacterial displacement by the new feed material added each day. This is called the "washout point" and is usually considered as the point at which an increase in the volumetric feed rate to the digester results in a decrease in the total biogas production and volatile solids removal efficiency. The hydraulic retention time or the volumetric loading rate to the anaerobic digester must be longer than the "washout" retention time to maintain stable digester operation.

For concentrated wastes such as beef and dairy manure, the organic loading rate limitation is reached before the washout hydraulic retention time. However, in dilute wastes, such as swine manure or manure from a flushed barn operation, the hydraulic washout point may occur before the organic loading becomes limiting.

To provide a design that will maximize the energy production for any anaerobic digestion system, the anticipated volumetric loading and organic (volatile solids) loading levels must be established. The available design information for swine operations at the present time is extremely misleading.

Table 5 summarizes some of the standard sources of manure production and characterization data for swine operations. The last column summarizes the data available from the monitoring program at Linden Lee Farms. The second-to-last column is data collected from Selves Farms Ltd., a 375 sow farrow-to-finish swine operation adjusted to the appropriate live weight of 120,000 kg. The main sources of literature agree with each other, but do not agree with any of the collected data at Selves Farms or Linden Lee Farms.

The difficulty in separating the quantities and concentrations of manure from the various sources at Linden Lee Farms make calculation of the loading rate difficult and inaccurate. However, the data collected at Selves Farms appears to support the approximations made during this study.

The design of anaerobic digesters and the sizing of electrical co-generation systems for swine operations is critically dependant on accurate organic and volumetric loading data. This information must be collected and published if systems similar to the Linden Lee Farms system are to be designed for other swine operations in Canada.

Engine Co-Generation System Sizing

The engine generator size was selected on the biogas production estimates calculated from volatile solids and volumetric manure production statistics in the literature summarized in Table 5 and from laboratory studies on swine manure (CANVIRO, 1982).

The reduced volatile solids loading observed during this monitoring program resulted in less than 40% of the predicted biogas production. The generation system was designed to operate continuously and generate an average of 25 kW-hr.

Internal combustion engines require approximately 40% of the full load fuel consumption to operate at the design engine speed with no load. As a result, the engine consumes all the fuel contained in the biogas storage tank in approximately 15 to 30 minutes and then shuts down. The anaerobic digester requires 15 to 30 minutes to produce enough gas to refill the storage tank after each shutdown. When the biogas storage tank is full, the engine restarts and runs for another 15 to 30 minutes. This continuous starting and stopping of the generation system makes the present system unworkable and modifications will be required in the near future.

TABLE 5. COMPARISON OF MANURE CHARACTERISTICS FOR A 2000 HEAD (120,000 kg live weight) GROWING AND FINISHING SWINE OPERATION FROM VARIOUS SOURCES

PARAMETER	AGRICULTURE CANADA	MID-WEST PLAN SERVICE	ASAE DATA	TURNBULL 1983	SELVES FARMS LTD. ***	LINDEN LEE FARMS
Manure Volume (L/d)	18,200	8300	7800	16,800	14,000	16,200 *
Moisture Content (%)	91	90.8	90.8	94	95.9	96.5
Dry Matter Content (%)	9.0	9.2	9.2	6.0	4.1	3.5
Volatile Solids Content (%)	6.8	6.9	7.4	4.5	2.9	2.4
Volatile Solid Production (kg/d)	576	572	576	756 **	313	Unknown
Energy Production Potential (GJ/d)	9.7	9.0	9.7	11.9	4.9	4.4

* Including the neighbouring swine and poultry operation
** Calculated only
*** Data from a recent study (CANVIRO, 1984) adjusted for 2000 head operation

5.0 ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM ENERGY BALANCE

A complete energy balance on the Linden Lee Farms anaerobic digestion and electrical co-generation system could not be performed because of the intermittant operation of the generation system during the monitoring program. Engine fuel consumption and heat recovery from the water jacket and exhaust gas could not be determined with any precision since the temperatures did not stabilize during the short operational cycle.

Table 6 summarizes the estimated electrical energy requirements to run the Linden Lee Farms anaerobic digestion and electrical co-generation system. A total daily power demand of approximately 133 kW-hr/d is required to operate the system. A conversion factor of 10,500 kJ/kW-hr was used to convert the electrical energy of 48,550 kW-hr/year to the thermal equivalent of 510 GJ/year. This conversion factor is generally used for power produced from hydraulic, nuclear, and purchased electricity. It is equivalent to the thermal energy required to produce 1 kW-hr of electricity at a coal burning power plant.

TABLE 6. ELECTRICAL ENERGY REQUIREMENTS FOR THE LINDEN LEE FARMS ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM

Manure Pumping	(10 HP x 1 hr/d)	8	kW-hr/d
Anaerobic Digester Mixing	(6 HP x 24 hr/d)	107	kW-hr/d
Biogas Handling	(1.5 HP x 8 hr/d)	9	kW-hr/d
Heat Recovery System Pumps	(1/2 HP x 12 hr/d)	4.5	kW-hr/d
Instrumentation	(1.5A @ 120 V)	4.5	kW-hr/d
	Total Daily Demand	133	kW-hr/d
	Total Yearly Demand	48,550	kW-hr/d
	Energy Equivalent	510	GJ/year

Table 7 summarizes the manure heating requirements and anaerobic digester heat losses for the Linden Lee Farms anaerobic digestion and electrical co-generation system.

The calculations were preformed using a computer program (HEATTANK) and the average climatic data from the Charlottetown airport weather station.

TABLE 7. SUMMARY OF THE MANURE HEATING REQUIREMENTS AND DAILY DIGESTER HEAT LOSSES FOR THE LINDEN LEE FARMS ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION SYSTEM

ANAEROBIC DIGESTER DESIGN DATA	
Inside diameter of the digestion tank (meters)	7.3
Total height of digester walls (meters)	7.3
Digester side water depth (meters)	6.7
Digester wall thickness (centimeters)	20
Digester floor thickness (centimeters)	30
Digester roof thickness (centimeters)	15
Depth the digester is buried below grade (meters)	2
Insulation thickness below grade (centimeters of SM type)	5
Insulation thickness above grade (centimeters)	5
Insulation thickness on the roof (centimeters)	5

MANURE CHARACTERISTICS AND DESIGN DATA	
Maximum daily volume of manure pumped (L/d)	16,200
Minimum manure temperature (degrees C)	5
Maximum manure temperature (degrees C)	15

DESIGN OPERATING CONDITIONS	
Digester operating temperature (degrees C)	35
Design minimum ambient air temperature (degrees C)	-10
Design maximum ambient air temperature (degrees C)	18
Design minimum earth temperature (degrees C)	1.0
Design maximum earth temperature (degrees C)	13.8
Design wind velocity (km/hr)	20

SUMMARY OF THE DIGESTER TANK HEAT LOSSES

HEAT LOSS	SURFACE AREA (square meters)	MAXIMUM (GJ/d)	MINIMUM (GJ/d)	AVERAGE (GJ/d)
Digester floor	53.1	0.096	0.064	0.080
Digester wall below frost	14.7	0.027	0.018	0.023
Digeter wall in frost	29.5	0.060	0.037	0.048
Digester wall liquid section	118	0.325	0.128	0.226
Digester wall gas section	14.7	0.037	0.014	0.025
Digester roof	90	0.228	0.090	0.159
TOTAL LOSSES	320	0.773	0.351	0.561

SUMMARY OF MANURE HEATING REQUIREMENTS

	VOLUME (m^3/d)	MAXIMUM (GJ/d)	MINIMUM (GJ/d)	AVERAGE (GJ/d)
Manure heating	16.3	2.06	1.24	1.65
TOTAL HEATING LOAD	(GJ/d)	2.83	1.59	2.21

The manure heating requirements were calculated using the average measured manure volume pumped to the digester during the monitoring program. The specific heat (CP) of water at the same temperature as the manure was used in the calculation.

The digester heat losses were calculated using the January and July air and soil temperature and a wind velocity of 20 km/hr. The digester is buried 2 meters below grade and extends 5.3 meters above grade.

6.0 ECONOMIC EVALUATION

6.1 Capital Costs

A summary of the Capital Costs for the Linden Lee Farms Anaerobic Digestion and Electrical Co-generation System are shown in Table 8. The capital costs have been summarized under the various components of the system and the percent of the major component costs and the total capital cost have been calculated, and are included in the table.

As indicated in Table 8, modification of the existing manure handling and collection system was necessary to bring the manure from the neighbouring barn located 1 km away.

Most of the equipment purchased for the biogas safety and biogas utilization system represent the smallest commercially available components for continuous industrial use. These components are still larger than necessary for a 1400 head finishing hog operation. The major components of the system are capable of processing manure from a 3500 head finish operation with very little modification. The total capital cost for this system represents the approximate capital costs for a system capable of processing the manure from a 3500 head swine finishing operation.

6.2 Operation and Maintenance Costs

The delay in the performance monitoring program caused by the fire that destroyed the workshop and electrical-cogeneration system and subsequent problems with the volatile solids production, resulted in insufficient data on the operation and maintenance requirements of the system to estimate the operational cost. Longer term monitoring and evaluation will be required to obtain these costs.

6.3 Cost Savings

At the time of preparation of this report, an estimate of the cost savings could not be made from the information obtained during the part time generator operation. Modifications to the existing system will be required before cost savings can be determined.

TABLE 8. CAPITAL COSTS FOR LINDEN LEE FARMS ANAEROBIC DIGESTION AND ELECTRICAL CO-GENERATION FACILITY

	ACTUAL COST	% OF MAJOR CAPITAL	% OF TOTAL CAPITAL
Manure Feed System			
Manure Feed Pumps	$ 6,743.00	5.2	4.0
Manure Transfer Line	5,305.00	4.1	3.2
SUBTOTAL	$ 12,048.00	9.3	7.2
Digestion Tank System			
Digestion Tank	$ 35,031.00	27.2	21.1
Heat Exchange Coils	3,612.00	2.8	2.2
Mixing System	12,522.00	9.7	7.5
Insulation	7,453.00	5.8	4.5
Gas & Hot Water Piping	7,921.00	6.2	4.8
SUBTOTAL	$ 66,539.00	51.7	40.1
Biogas Storage & Utilization System			
Biogas Storage	$ 4,212.00	3.3	2.5
Biogas Blower	2,903.00	2.3	1.7
Engine Generator & Biogas Fuel Train	38,910.00	30.2	23.4
Heat Recovery System	4,117.00	3.2	2.5
SUBTOTAL	$ 50,142.00	39.0	30.2
MAJOR CAPITAL SUBTOTAL	$128,729.00	100.0	
Site Work	$ 1,400.00	1.0	0.8
Mechanical Installations	3,181.00	2.5	1.9
Electrical Installations	16,160.00	12.5	9.7
Engineering Design	16,500.00	12.8	9.9
TOTAL CAPITAL COST	**$165,970.00**	28.8	99.8

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following conclusions have been drawn from the operation and monitoring of the Linden Lee Farms Anaerobic Digestion and Electrical Co-Generation System:

(1) The anaerobic digestion process can be applied effectively to the digestion of swine manure. The digestion process produces large quantities of high quality (60% methane) biogas. The specific gas production rate during the monitoring program remained consistent at 0.30 m^3 biogas/kg VS fed/day (0.18 m^3 CH_4/kg VS fed/day). This rate is considerably different than the 0.7 m^3 biogas/kg VS fed/d observed at Selves Farms Ltd. (CANVIRO, 1984).

(2) The anaerobic digestion system operated under very stable conditions during the monitoring program with an average hydraulic retention time of 18 days and a volatile solids loading rate of 1.35 kg VS/m^3/d.

(3) The currently published volatile solids production statistics as published by Agriculture Canada (1981) may over estimated the volatile solids produced at Linden Lee Farms by 149%. Adequate data was not available to verify this production rate, however data at Selves Farms Ltd. (CANVIRO, 1984) indicated a 186% over estimate of volatile solids production.

(4) Biogas produced from the anaerobic digestion system can be used to fuel a natural gas internal combustion engine and produce electrical power. The energy conversion efficiency observed during the monitoring program was approximately 14,960 kJ/kW-hr.

(5) A significant amount of heat can be recovered from the internal combustion engine, but the intermittent operation of the engine generation system made estimating the heat recovery impossible during the monitoring program.

(6) The final effluent from the digestion system is slightly more liquified than the original manure and still contains all of the

nitrogen of the original manure. This liquid effluent can be irrigated or spread with only a fraction of the odour normally associated with manure spreading.

7.2 Recommendations

Based on the information collected during this monitoring program, the following recommendations are proposed:

(1) A longer term, more intensive monitoring program to establish the actual volatile solids production from intensive swine units is required. A correlation of animal populations, volatile solids production and biogas production is essential to the designers of future anaerobic digestion and electrical co-generation systems. The sizing of any biogas utilization system is critically dependant on this information.

(2) Modifications to the existing Linden Lee Farms electrical generation system will have to be made to compensate for the lower than anticipated biogas production. This will be accomplished by lowering the engine speed from 1800 RPM to 1200 RPM and changing the generator from a 40 kW-hr to 20 kW-hr.

(3) After the modifications to the Linden Lee Farms electrical generation system have been complete, a comprehensive evaluation of the energy consumption, energy production and heat recovery and utilization system should be conducted. Heat recovery from the engine for most farm scale co-generation units make a significant contribution to the economic feasibility of the overall anaerobic digestion and electrical co-generation system.

4) Long term monitoring of the total system to determine the reliability of the various components should be conducted. This information will be valuable to the designers of future systems.

5) Research into lower cost electrical generation units and/or biogas utilization alternatives with higher economic returns should be conducted.

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